

LABORATORY SIMULATIONS TO EXPLORE THE STRENGTH OF DEEPLY BURIED PVC SEWERS UNDER VERTICAL RISERS UNDER VERTICAL RISERS

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ABSTRACT

Vertical risers are service lines that connect directly into the top of horizontal sewer pipes. These structures are known to be susceptible to fracture under vertical forces that develop in the riser due to downdrag of trench backfill. To study the stability of deeply buried PVC sewers under vertical risers, the strength of existing PVC sewers must be established. While it is relatively straightforward to study fitting strength in isolation, it is considerably more difficult to define the performance of PVC sewer fittings when buried. This paper reports on laboratory simulations investigating the capacities of existing Tee fittings when buried in uniform sand.

RÉSUMÉ

Les colonnes montantes sont des tuyaux de service qui sont connectés directement au dessus des conduits d'égout horizontaux. Ces structures sont connues d'être susceptibles de rupture sous les forces verticales qui se développent dans la colonne dues au frottement négatif du remblai de tranchée. Pour étudier la stabilité des égouts en PVC profondément enterrés et connectés aux colonnes montantes, la résistance des égouts en PVC existants doit être établie. Tandis qu'il est relativement facile d'étudier la résistance des raccords en isolation, il est considérablement plus difficile de définir la résistance des raccords d'égout en PVC une fois enterrés. Cet article rend compte d'une simulation de laboratoire pour étudier les capacités des raccords existants en forme de T une fois enterrés dans un sable uniforme.

1 INTRODUCTION

The design of deeply buried riser connections is a challenging engineering problem that has received no attention from the research community. There are four current methods often used in practice to address the sewer riser problem, as illustrated in Figure 1. However all these methods shares common disadvantages.

Firstly, all of these current methods are designed with horizontal portions between main lines and drop laterals, which are laid over disturbed materials that may experience loss of bedding support if the foundation

settles. This may lead to a loss of grade and ultimately shear failure in the pipes or fittings.

Secondly, to minimize the effect of vertical force from the risers, measures such as sleeves and concrete encasement, may be designed and employed. These obviously increase project cost.

Finally, with the consideration of horizontal portions and the trench slope for the attachment of drop laterals, the excavation for service lines increases substantially when mainlines are deeply buried. This greatly adds to construction cost and time.

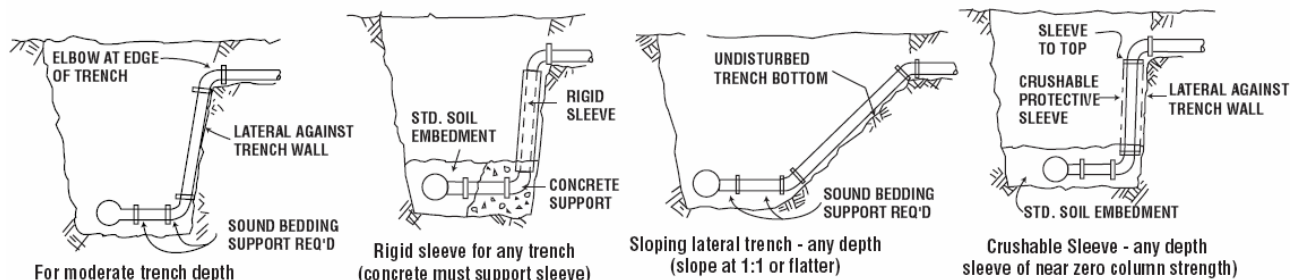


Figure 1. Current methods used in practice (from IPEX, 1999)

Therefore contractors tend to connect service lines to mainlines using vertical risers, as shown in Figure 2.

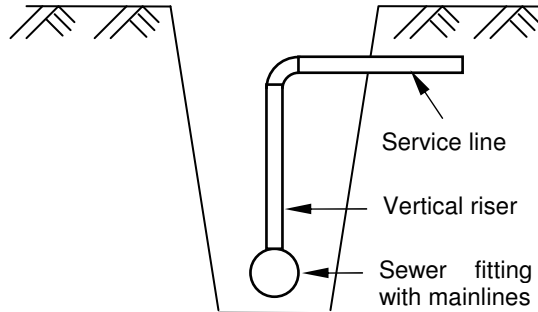


Figure 2. Service line connected with vertical riser

However, downdrag develops around the vertical riser as backfill is placed in the trench, and large vertical forces may then act on the fittings. Even if each fitting from the manufacturer is clearly marked to dissuade contractors from using this configuration, the potential savings in excavation costs mean that contractors persist with this practice and failures sometimes result. The objective of the present project is to determine the strength (resistance) of the buried fittings to this vertical force, and the vertical forces (demand) that are expected in various different burial conditions. If new fittings or configurations can be developed to resist this force (or compliant fittings can be used to eliminate the force from the vertical riser), it will lower project cost, shorten construction time, save construction space, and avoid litigation and costly repairs when contractors fail to heed the moratorium on this practice.

This paper describes the laboratory test program to explore the strength (resistance) of existing Tee fittings under the downdrag forces along vertical risers when buried in sand backfill.

2 LABORATORY FACILITY FOR BURIED FITTING TESTS

Buried fitting tests were performed in the biaxial cell at Queen's University, which was originally developed by Brachman et al. (1999). Since the biaxial cell is only 1.6m high and this is not enough to simulate loads associated with deep burial (of say 10m), a new testing configuration was developed after modifying the existing facilities.

Now, two types of loads develop on the buried fitting system. The first set of loads is associated with the earth pressures acting around the fitting. The second is the axial force from the riser on the top of the fitting as a result of the downdrag force imposed on the riser. To simulate field conditions, both of these loads need to be applied simultaneously during testing. The biaxial cell

uses an air bladder to simulate overburden pressures and this generates vertical and horizontal earth pressures on the buried fitting. The axial force from the riser to the fitting is also needed, and this was applied using a hydraulic actuator. An existing steel reaction frame was modified and the actuator was mounted above the lid of the cell. The force was applied using a rod protruding through a hole cut in the biaxial cell lid. A special steel clamp plate was designed to seal the bladder around that aperture. The loading rod and a rod guiding plate were also fabricated to satisfy the testing and safety requirements. Two dozen engineered C-clamps attached the actuator frame to the top of the biaxial cell lid. The final configuration is illustrated in Figure 3.

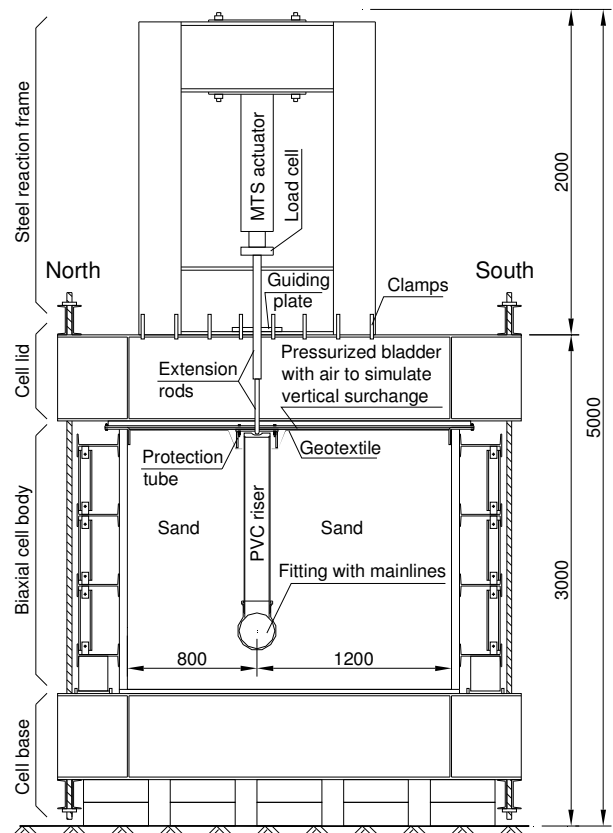


Figure 3. Test facility showing pipe and fitting configurations, and the actuator location

3 TEST PROCEDURES

3.1 Test conditions

The biaxial cell was originally designed for laboratory simulations of embankment burial conditions. Friction treatment is employed on the cell walls, to limit the friction angle between the backfill and the steel cell walls to less than 5 degrees. Current design of buried thermoplastic pipes almost always ignores the benefits of trench

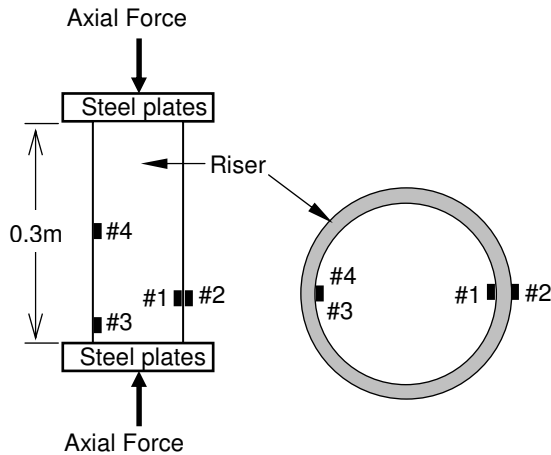
conditions, since this provides conservative solutions and avoids potential problems if shear stresses on the sides of the trench do not last over the long term. The cell was therefore used to simulate embankment loading conditions in this study of fitting performance under vertical risers.

The test facility shown in Figure 3 was used to perform the tests for both Tee and Wye fittings. Since the testing configurations, testing procedures, and analyses for the results are similar, the following description and discussion are focused on the Tee fittings. The actual length of the buried riser section within the soil was 1.0m though the force applied by the actuator simulates the load that develops on a much deeper structure.

Prior to the buried fitting tests, the existing PVC fittings (i.e. Tee and Wye) were tested in isolation using universal testing machines. These tests indicated that the capacity of the existing PVC Tee fitting to resist vertical force from a riser without lateral soil support (in isolation) was approximately 9kN.

3.2 Calibration Tests

To be able to determine the axial forces that develop on the fitting, two preliminary calibration tests were performed on the riser alone, loaded along its axis in a universal testing machine. These tests featured axially oriented strain gages attached to the riser, Figure 4.



a. Vertical section b. Horizontal section
 Note: Gages #1 and #2 were attached 80mm from the riser base; Gage #3 was attached 20mm from the riser base, Gage #4 was attached 150mm from the base. Gages here were all axially oriented.

Figure 4. Configuration of the calibration test using a 300mm section of riser (not to scale)

The purpose of these two calibration tests was to establish the relationship between axial strains and axial forces in the riser, so that the riser could be used like a

load cell. During the buried fitting tests, the axial strains near the bottom of the riser were measured using axial strain gages at that position. The axial strains from the buried fitting tests were then used to calculate the corresponding axial forces, using the relation between axial strains and axial forces of the riser determined during riser calibration.

The length of the riser was 300mm for one calibration test and 200mm for another. Both tests implied that the relation between axial forces and axial strains on the riser was approximately linear when the axial forces were less than 60kN. Curves of axial forces versus axial strains from the 300mm-long riser test are shown in Figure 5.

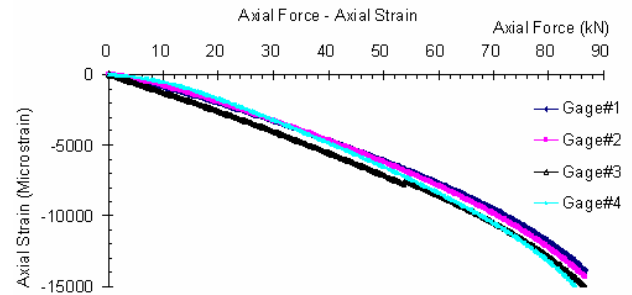


Figure 5. Results from the 300mm-long riser test

The average slope of the curves before 60kN of axial force in Figure 5 is 121.40 microstrain/kN. The average slope of the curves from the second test is 124.30 microstrain/kN. The difference between these two slopes is small implying the riser length had little effect on calibration. A cubic polynomial was used to fit for the axial strains from both calibration tests, as shown in Equation 1. The R-squared value (coefficient of determination) of this correlation, $R^2=0.998$, is very close to 1, indicating that Equation 1 fits these data very well. This expression provides axial forces, when axial strains in the risers are measured during buried fitting tests.

$$F_a = -3 \times 10^{-11} \times \epsilon_a^3 - 5 \times 10^{-7} \times \epsilon_a^2 - 0.0101 \times \epsilon_a \quad [1]$$

where, F_a are the axial forces and ϵ_a the axial strains.

3.3 Instrumentation

Instrumentation used in the buried fitting tests included strain gages, linear potentiometers (LPs), one digital camera, settlement plates, and earth pressure cells.

Four strain gages were located evenly around the riser circumferentially, attached to the inside surface at the riser base prior to burial. Two gages were located at the top end of the riser, spaced evenly in the circumferential direction (at opposite sides). Axial forces were determined from axial strains at the riser base; forces of this magnitude acting down on the top of the fitting.

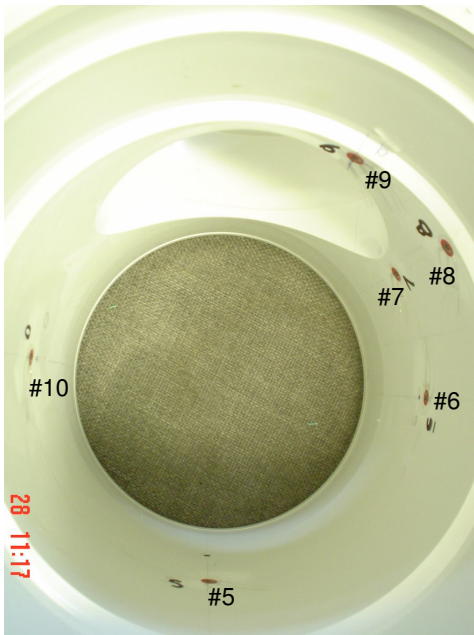
Ten rectangular, triaxial strain gage rosettes were attached to the buried fitting to investigate local response and to determine weak zones in the buried fitting under load. These rosettes were attached at the critical locations determined in the fitting-only tests. Six rosettes were attached inside the fitting and four rosettes were attached outside the fitting, as shown in Figure 6.

Two linear potentiometers (LPs) were installed to measure the changes in vertical and horizontal diameters in the horizontal cylinder section of the fitting. The horizontal diameter change was monitored using LP denoted LPh. The vertical diameter change was measured using LP denoted LPv.

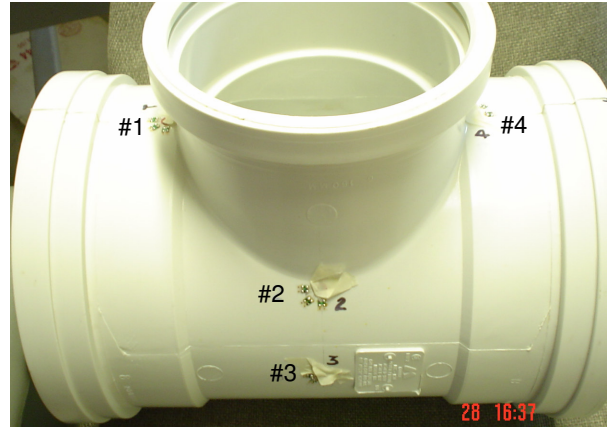
A digital camera was set to monitor the deformations of the horizontal pipe section of the fitting. A foam ring attached inside the fitting acted as visual targets. The LPs and camera targets are shown in Figure 7.

Two settlement plates were installed to measure the vertical deformations of the sand under the overburden pressure applied using the air bladder. One settlement plate was initially set 0.25m above the cell bottom plate, the same elevation as the invert of the horizontal sewer. Another plate was set 0.5m above the cell base plate, the same elevation as the crown of the horizontal sewer.

Four earth pressure cells were buried in the soil to measure the vertical and horizontal earth pressures. Two pressure cells were buried 0.5m above the cell base, one oriented horizontally and the second vertically. A further two pressure cells were positioned 1.2m above the cell base in horizontal and vertical orientations.



a. Six rosettes attached inside the Tee fitting



b. Four rosettes attached outside the Tee fitting
Figure 6. Strain rosettes attached on the Tee fitting

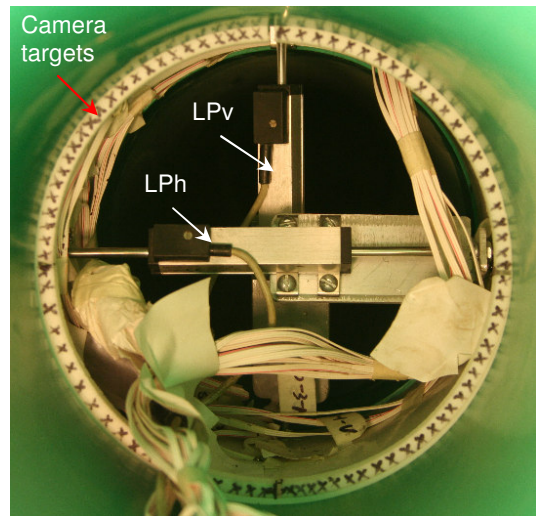


Figure 7. Setup of LPs and camera targets

Analysis of data acquired from the settlement plates and earth pressure cells indicates that the initial constrained modulus (M_s) of the sand around the Tee fitting was 11.5MPa.

One air pressure transducer was used to monitor air pressure in the bladder and a load cell was used to measure the load applied by the actuator. The actuator stroke was also recorded by the data acquisition system.

3.4 Test configuration

The PVC sewers were buried in the cell filled with uniform synthetic olivine sand. A 10" X10", 12lb tamping tool was dropped from 15 to 20cm height to compact the sand. The bedding sand was compacted in three passes and the remaining sand was compacted once. After compaction, the total unit weight of the bedding was 15.1kN/m³ at an average water content of 1.5%, and that of the remaining fill was 14.4kN/m³ at an average water content of 3.5%.

When the cell was full of sand, the cell lid was installed and the actuator and the reaction frame were mounted on the top of the cell lid. The hydraulic actuator was connected to an oil pump via a controller and oil lines. The air bladder was connected to the high-capacity air pump via an air-controller and air lines.

Two testing modes can be realized by the facility shown in Figure 3. One mode involves changing simultaneously the overburden pressures applied using the air bladder and the axial forces applied using the actuator. A second mode involves keeping overburden pressure constant, by fixing air pressures in the bladder, and then changing magnitude of axial force using the hydraulic actuator. During the Tee fitting test the former mode was investigated; however the latter mode was mainly used. When the former mode was adopted, the uniform overburden pressure and the axial force were applied simultaneously in accordance with the prescribed load steps. When the latter mode was used, the overburden pressure was kept at a constant magnitude (of say 173kPa) and the actuator was then increased to a designated value of axial force or until fitting failure.

4 RESULTS FROM BURIED TEE FITTING TESTS

4.1 Test Objectives

Two objectives were defined for the buried Tee fitting tests. The first objective was to explore the strength of the buried Tee fitting. The second was to study the local response and locate the weakest zones in the existing Tee fitting when buried.

4.2 Strength of Buried Tee Fitting

When the overburden pressure was kept constant at 173kPa during the buried fitting test, the system was not brought to failure even though the load from the actuator reached 50kN. However, the axial force on the top of the fitting calculated from the axial strains on the riser base was only 33.0 kN. This indicates that the accumulated skin friction along the 1m-long riser was around 17.0kN, acting upwards on the riser. The allowable load capacity of the reaction frame was reached and the test was terminated at actuator load of 50kN. The next test stage involved bringing the buried Tee fitting to failure by increasing axial force from the actuator while no overburden pressure acted on the top of sand. Eventually the fitting failed at an actuator load of 48.8kN, corresponding to axial force on the top of the fitting of 43.6kN (calculated using axial strains measured at the base of the riser). The accumulated skin friction along the 1m-long riser was therefore approximately 5.2kN, acting upwards on the riser.

The friction force of 5.2kN implies a secant residual horizontal (lateral) earth pressure of 23.5kPa around the 1m-riser after removal of the maximum overburden pressure of 173kPa, assuming a friction coefficient of 0.44 between PVC and uniform sand (based on tests reported by El Chazli et al., 2005). This could have

increased the capacity of the 1m-deep buried Tee fitting due to increased density and stress in the surrounding soil. Results from the Tee fitting tests are summarized in Figure 8, including results of the fitting-only test.

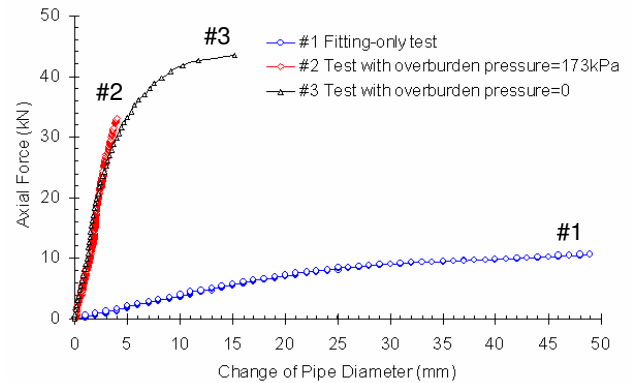


Figure 8. Results of Tee fitting tests

Curve #1 shows results for the fitting-only test performed earlier. Initial yield in the fitting occurred at vertical riser load of approximately 9kN and a change in vertical diameter of the horizontal pipe section of around 25mm. Curve #2 presents the results from test with both overburden pressure and axial force increasing simultaneously. Once overburden pressure reached 173kPa, it was kept constant while the actuator increased further to 50kN and the test was terminated. Curve #3 provides results for the test on the buried Tee without applied overburden pressure. The fitting fractured after the actuator load increased to 48.8kN. The change in vertical diameter of the horizontal pipe section of the fitting was 4mm at initial yield, and 15mm at fracture.

Figure 8 shows that the slope of the straight section of Curve #2 is 8.8kN/mm, and the slope of the straight line section of Curve #3 is 8.0kN/mm. Overburden stresses associated with Curve #2 are equivalent to fitting burial of 13m in sand, and overburden stresses associated with Curve #3 are equivalent to fitting burial of 3m. The small difference between these two slopes indicates that burial depth has a small effect on stiffness. So, once the fitting is buried in dense soil, its stiffness does not vary significantly with burial depth.

Curve #3 shows that the strength of the Tee fitting buried in 1m depth of sand is approximately 43.6kN. The strength of the Tee fitting at depth of 13m is not obvious from Curve #2, since the fitting did not crack during this stage of the test. Since Curve #2 has the same trend as Curve #3, the estimated strength of this Tee fitting is estimated as between 40kN and 45kN for burial depth of less than 13m. This is approximately 4.5 to 5 times that of the fitting tested in isolation.

4.3 Local Response of the Tee Fitting

To study the local response of the Tee fitting, circumferential strains at an axial riser force of 5kN applied to the top of the fitting are provided in Table 1.

For convenience, the circumferential strains listed in Table 1 are also marked on sketches shown in Figures 9 and 10. The gage locations in the fitting-only test were slightly different from those in the buried fitting test. Please refer to Table 1 and Figures 9 and 10 for these differences.

Table 1. Circumferential strains at an axial riser force of 5kN on the Tee, and overburden pressure of 173kPa

Fitting-only test		Buried fitting test with overburden pressure of 173kPa	
Gage No.	Strains (%)	Gage No.	Strains (%)
#1	-0.09	#1/#4	+0.00 / Damaged
#2	-1.31	#2	Damaged
#3	0.56	#3	0.03
#4	0.94	#5	-0.01
#5	-0.71	#6/#10	-0.20 / -0.18
#6	0.43	#7	0.15
#7	0.05	#8	-0.13
#8	Damaged	#9	-0.06
#9	0.08	N/A	/
#10	0.76	N/A	/

¹Note: Refer to Figures 9 and 10 for gage locations. Gage numbers at the same row in the table indicate that these gages were at the same or similar locations on the fittings. Negative values correspond to compression.

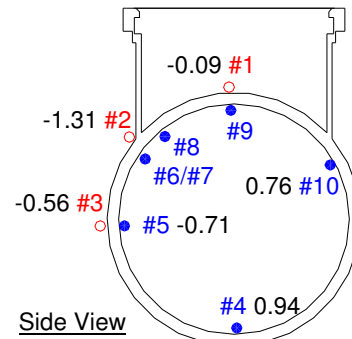
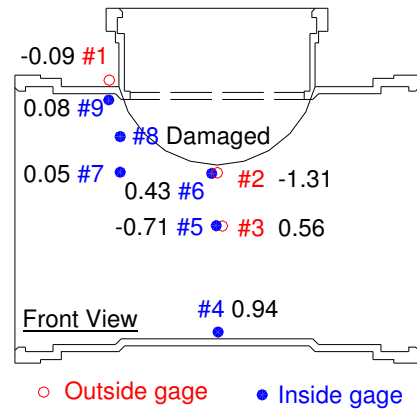


Figure 9. Circumferential strains at the axial riser force of 5kN in the fitting-only test (% strain)

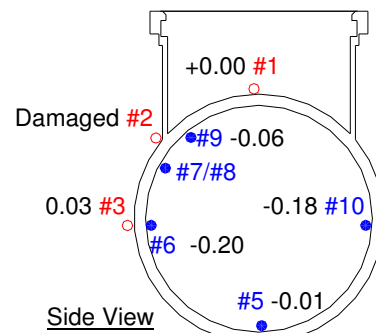
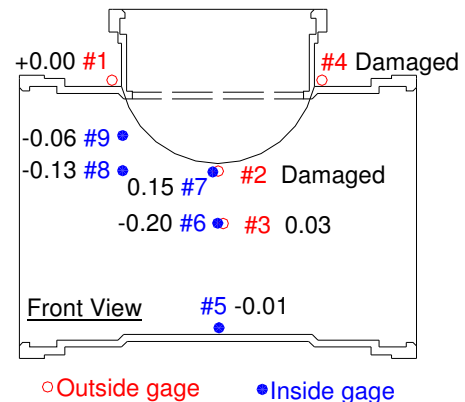


Figure 10. Circumferential strains at a axial riser force of 5kN acting on the Tee fitting tested in the buried condition with overburden of 173kPa (% strain)

When supporting an axial riser force of 5kN, the vertical diameter change of the horizontal cylinder section in the fitting-only test was 13mm, and that in the buried fitting test was just 0.55mm. As illustrated in Table 1 and Figures 9 and 10, the local responses of the fitting in isolation and when buried in soil are quite different. Firstly, the local circumferential strains in the fitting-only test were generally greater than those during the buried fitting test. Secondly, in both the fitting-only test and the buried fitting test, the circumferential strains were generally greater than the axial strains except those at the crown, such as Gage #1. This implies that in both tests, the fitting primarily deforms by circumferential bending in the horizontal cylinder section. Finally, in the fitting-only test, local strains in the upper half had magnitudes close to those at the corresponding locations in the lower half. However, in the buried fitting test, the local strains in the upper half were generally much greater than those at the corresponding locations in the lower half. Soil support under the lower half of the buried fitting is likely the major factor causing this difference.

Overall, the surrounding soil changed the boundary condition of the buried fitting and then changed its local response. Since the outside of the fitting was constrained by the surrounding soil, smaller strains were generated on the outside surface of the fitting when buried. Similarly the lower part of the fitting was restrained by the soil so that in general the strains in the lower half were smaller than those in the upper half.

4.4 Deformed Shapes of Horizontal Cylinder Section

In the fitting-only test, the transverse section of the part of the fitting that is a horizontal cylinder deforms into an ellipse; deformations are symmetrical about both the vertical and horizontal axes, Figure 11.

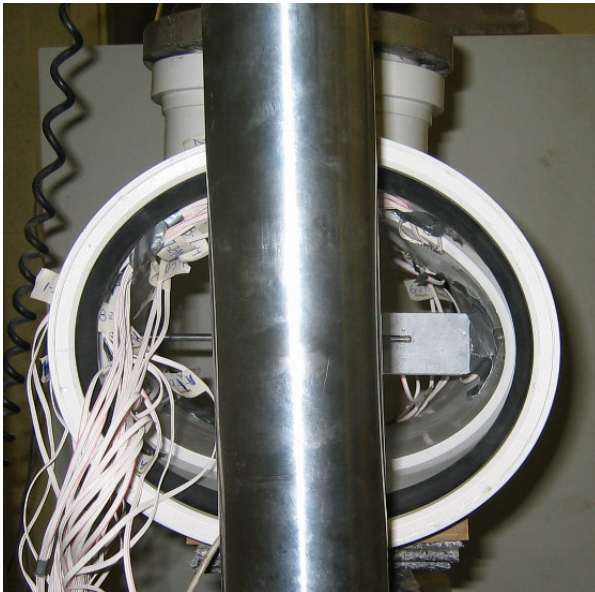


Figure 11. Deformed shape in the fitting-only test

In the buried fitting test the deformed shape of the horizontal pipe section of the fitting was different to that shown in Figure 11. The deformation is no longer symmetrical about the horizontal axis, since deformations in the upper half are much greater than those in the lower half, Figure 12. The upper half of the buried fitting appears more susceptible to failure as a result of bending, while soil support for the lower part leads to reduced bending response.

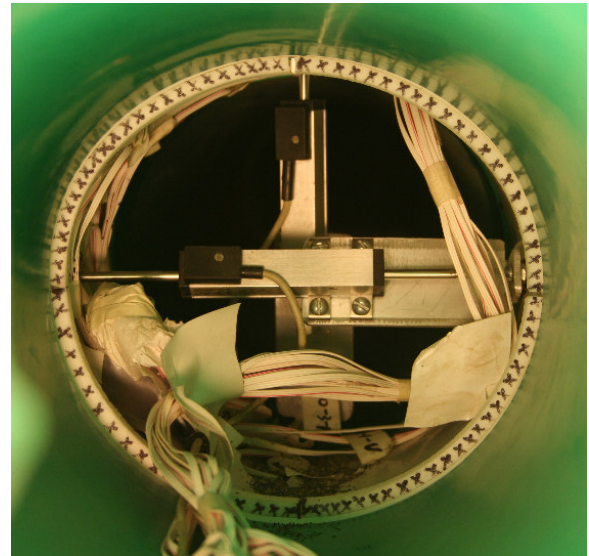


Figure 12. Deformed shape right before the fitting cracked in the buried fitting test

The deformed shapes of the horizontal cylinder section of the fitting are summarized in Figure 13. Here the axial force on the buried fitting was 37.6kN and that on the fitting tested in isolation was 8.4kN.

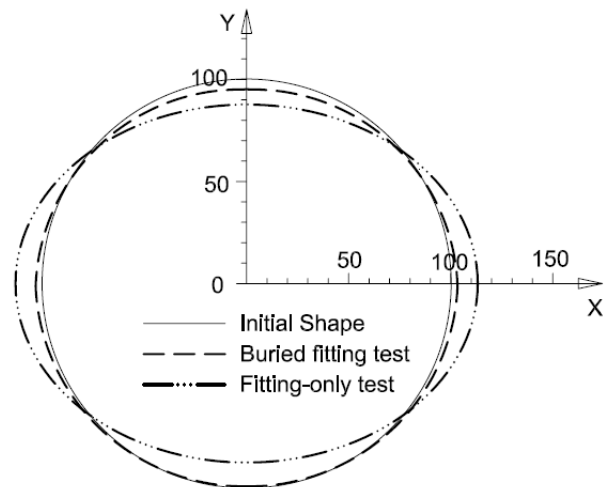


Figure 13. Deformed shapes of horizontal pipe (mm)

4.5 Fitting fracture

The fractured sample following exhumation of the buried fitting test is shown in Figure 14. A fracture occurred around the base of the vertical riser, as the riser punched down through the top of the fitting. No fracture was observed in the lower half of the fitting. These results are consistent with the strains collected from rosettes attached to the fitting. For example, the absolute values of the circumferential strains at Rosettes #2, #4 and #7 attached near the base of the vertical riser shown in Figure 6 were all over 1.6%, while those at Rosettes #5, #6 and #10 located on the lower half of the fitting were all less than 0.8%. The buried fitting exhibited brittle response that was different to the ductile behaviour observed during the fitting-only tests.



Figure 14. Fractured Tee fitting in sand

5 SUMMARY AND CONCLUSIONS

To explore the strength of deeply buried PVC sewers under vertical risers, new laboratory test procedures were developed by modifying the existing buried pipe testing facilities in the GeoEngineering laboratory at Queen's University. Both PVC Tee and Wye fittings were tested using these new procedures. The laboratory procedure involves using a 1.6m-high pipe test cell to explore the capacity of PVC fittings at burial depths equivalent to over 10m.

Tests on the Tee fitting are described here. The test results indicate that the load capacity of this existing Tee fitting when buried ranges from 40kN to 45kN, which is over 4.5 times that of the Tee fitting when it is tested in isolation. Failure of the buried Tee fitting was by fracture around the base of the riser, and at a relative low deformation, while the fitting in isolation appeared to respond in a ductile manner after yielding at relative high deformations.

The difference between the loads applied by the actuator and the axial forces calculated from axial strains measured at the base of the riser results from upward skin friction that develops along the riser. This indicates that the test facility might also be used to study the

friction behaviour between soils and PVC risers or other underground structures.

ACKNOWLEDGEMENTS

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